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ADVANCE CONFIDENTIAL REPORT

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By Robert W. Byrne

SUMMARY

An investigation has been conducted to determine the possible extent of effects of wind-tunnel constriction at high speeds for airfoils of various thickness-to-chord ratios at or near zero lift. The results indicate that a limiting test Mach number exists which is principally a function of the ratio of model thickness to tunnel height. At high Mach numbers serious constriction effects occur; these effects are of such a nature that the standard calibration methods give speeds much lower than the actual test speeds.

INTRODUCTION

Considerable theoretical work has been done on low-speed wind-tunnel-wall interference, and ordinary constriction corrections have been applied to wind-tunnel results at low speeds. Little is known, however, about the tunnel-wall effects for speeds at or greater than the model critical speeds. An investigation has therefore been made in the Langley 24-inch high-speed tunnel to determine the possible increase in magnitude of constriction effects at high speeds and the limitation on the maximum speed at which a model could be tested.

In this investigation, the Mach numbers existing at the test-section walls of the tunnel along a line parallel to the tunnel axis and opposite the midspan of the model were measured to provide comparison with the standard calibrated static-pressure orifices used for speed determination. The measurements were made with the tunnel empty and with several models of varying size and thickness ratio installed in the test section. The range of Mach numbers extended from 0.4 to the maximum Mach

numbers obtainable with most of the models. All measurements were made for lift coefficients of the model at or near zero.

APPARATUS AND METHODS

The five airfoil sections tested were the NACA 16-106, the NACA 16-215, the NACA 16-130, and the NACA 0012 airfoil sections with 5-inch chords and the NACA 0012 airfoil section with 2-inch chord. In the present tests, the circular test section of the Langley 24-inch high-speed tunnel (reference 1) was modified by flats, which reduced the span of the model to 18 inches, as shown in figures 1 and 2. The models spanned the test section between the flats and passed through holes in the flats. These holes were of the same shape as the model but were cut to provide a $\frac{1}{32}$-inch clearance completely around the model, which was supported externally on the Langley 24-inch high-speed-tunnel balance. (See fig. 1(a).)

Mach numbers at the wall were determined from measured values of the total pressure and from pressures measured by static-pressure orifices located in the tunnel wall in the plane of symmetry of the model. Free-stream Mach numbers were determined from measured values of the total pressure and from pressures measured by calibrated static-plate orifices located upstream of the test section. The orifices, located as shown in figure 2, were connected to a photorecording multiple-tube manometer.

The models were tested over a speed range from a Mach number of 0.4 to the highest Mach numbers of the tunnel, the top speeds varying with the size of each model. All airfoil models were tested at an angle of attack of 0° which, for the low-cambered airfoils used in this investigation, was at or near the zero-lift condition.

RESULTS

For presentation of the data obtained from the present tests, the following symbols are used in this report:

t profile thickness of model

h mean height of tunnel obtained by dividing tunnel area by model span

M_I Mach number at test section indicated by calibrated static-pressure orifices located upstream of test section

M_W Mach number indicated by static-pressure orifices in wall of test section in plane of symmetry of model

M_{cr} critical Mach number

The longitudinal Mach-number gradients along the tunnel wall, with and without a model installed, are shown in figure 3 together with the Mach numbers indicated by the calibrated static-pressure orifices M_I. All values of Mach number were determined by the usual methods from measured values of the static pressure and the total pressure. The flagged test points are for measurements at the rear wall.

The variation in the maximum Mach number at the tunnel wall opposite the model with the indicated Mach number for various ratios of model thickness to tunnel height is shown in figure 4. The maximum indicated Mach numbers are shown in figure 5.

DISCUSSION

The determination of speed in wind-tunnel test sections in all normal operations is made from measurements of the pressure at calibrated static-pressure orifices placed far enough upstream of the model to be uninfluenced by the pressure field of the model. Calibrations of the static-pressure orifices are usually made with the tunnel empty. For tunnels of the type described in reference 1, the pressures indicated by the calibrated static-pressure orifices are a measure of the total mass flow through the test section (if constant values of temperature and pressure in the atmosphere, from which the air in the tunnel is drawn, are assumed). The maximum mass flow is obtained when a Mach number of 1.0 is reached at the throat. If the area of the throat of

any given wind tunnel is decreased while the Mach number at the throat is maintained at 1.0, the indicated speed will decrease. A model placed in a wind tunnel thus produces a reduction in the throat area and, consequently, changes in the tunnel calibration.

The basic data of this investigation (fig. 3) show that with the tunnel empty the largest variation in Mach number occurred at top speed and was approximately 0.5 percent of the free-stream value. With a model in the tunnel, no appreciable gradient occurred along the tunnel wall until some value of the indicated Mach number greater than the critical Mach number of the model was reached. At any speed between the critical Mach number and the highest Mach number obtainable in the tunnel, a tunnel-wall gradient appeared (fig. 3), the magnitude of which increased rapidly as the maximum indicated Mach number was approached. Force-test results obtained at or near the highest speeds reached in this investigation might be subject to errors caused by the large magnitude of the axial-pressure gradients.

The highest speeds obtainable in tests of the NACA 16-106 airfoil section with 5-inch chord and the NACA 0012 airfoil section with 2-inch chord were limited because of an effective constriction that occurred downstream of the model at the intersection of the test section and exit cone where regions of local sonic velocity occurred.

As the maximum speed was approached, a rapid increase in the difference between the maximum Mach number at the walls opposite the model and the indicated Mach number resulted, as shown in figure 4. Data taken for the NACA 16-series airfoils and for the NACA 0012 airfoils with 2-inch and 5-inch chords, when considered separately, show that this difference is principally a function of the ratio of model thickness to tunnel height.

The relative positions of the curves in figure 4, from left to right, correspond in general to decreasing ratios of model thickness to tunnel height and, therefore, suggest that the limiting test or indicated Mach number and constriction effects are determined principally by the throat restriction, as expressed by t/h. Fundamental considerations based on the one-dimensional or nozzle theory, which neglects the effects of model lift (approximately zero in the experiments reported herein) and the effects of the pressure field of the model, also show that

the limiting test Mach number is a function of the area restricted. The theoretical limiting test Mach number - that is, the indicated Mach number - for which a Mach number of 1.0 is obtained at the test section, has been calculated accordingly from the foregoing assumptions and is shown in figure 5 as a function of the ratio of model thickness to tunnel height.

The experimental values for the thicker airfoils gave maximum wall Mach numbers opposite the model, which were slightly less than 1.0, as seen in figure 3. A Mach number of 1.0 may have been reached, however, at some point between the orifices and, because of the nearly vertical slopes of the curves in figure 4, the highest indicated test speeds obtained in these tests may be assumed to be the actual limiting speeds obtainable for these airfoils. For the two thinner airfoils, the maximum obtainable speed was determined by the downstream constriction and the limiting speed was therefore obtained by extrapolation, as shown in figure 4. The values of the indicated Mach number obtained for the various models at these points have been plotted in figure 5 and the points fall very nearly on the curve.

The experimental results thus indicate that, for a given ratio of model thickness to tunnel height, the limiting test Mach number is given by the theoretical curve of figure 5. Since the flow is essentially one dimensional only at the limiting Mach number, for which condition a Mach number of 1.0 exists across the whole flow between the model and the tunnel walls, it can be seen that the one-dimensional theory can give approximate values of only the limiting test Mach number and cannot give proper corrections to high-speed wind-tunnel results at Mach numbers below the limiting test Mach number.

In the actual case, when a Mach number of 1.0 is reached at any point in the test section - for example, at a point in the pressure field of the airfoil - the stream tube passing through that point has its minimum area and maximum mass flow. An increase in the general mass flow would thus produce increases of speed at adjacent regions and actual expansion of the stream tubes in which a Mach number higher than 1.0 is reached. These conditions will rapidly lead to the establishment of a Mach number of 1.0 across the whole flow at the throat of the tunnel.

Evidence of this quick building up to sonic speeds is shown by the rapidly increasing slopes of the curves in figure 4 and the increase in the values of the axial pressure gradients in figure 3 as the speeds were increased from the critical Mach number of the airfoil to the limiting test Mach number.

An additional observation can be made from the results of this investigation. If one or more model-support struts are used when testing is at high speeds, constriction effects will probably be encountered at lower speeds than if struts are not used; these effects may produce changes of air-flow direction if the struts are unsymmetrically disposed to the air stream.

CONCLUDING REMARKS

Serious constriction effects occur in wind tunnels at high speeds. One effect is that the indicated speeds obtained with models installed in the tunnel correspond to higher speeds than the speeds found with the tunnel empty. The magnitude of the difference between indicated speed and actual speed, when the airfoil is at or near zero lift, depends upon the values of speed, of ratio of model thickness to tunnel height, and of critical speed of the model. As the speeds reach the limiting speed, force-test results obtained may be subject to error, as is indicated by the extent of the axial-pressure gradients encountered. A limiting speed for the tunnel will exist corresponding to an indicated Mach number less than 1.0, for which case sonic velocities extend from the model to the tunnel wall. The limiting test Mach number is in reasonable agreement with the Mach number indicated by the one-dimensional or nozzle theory.

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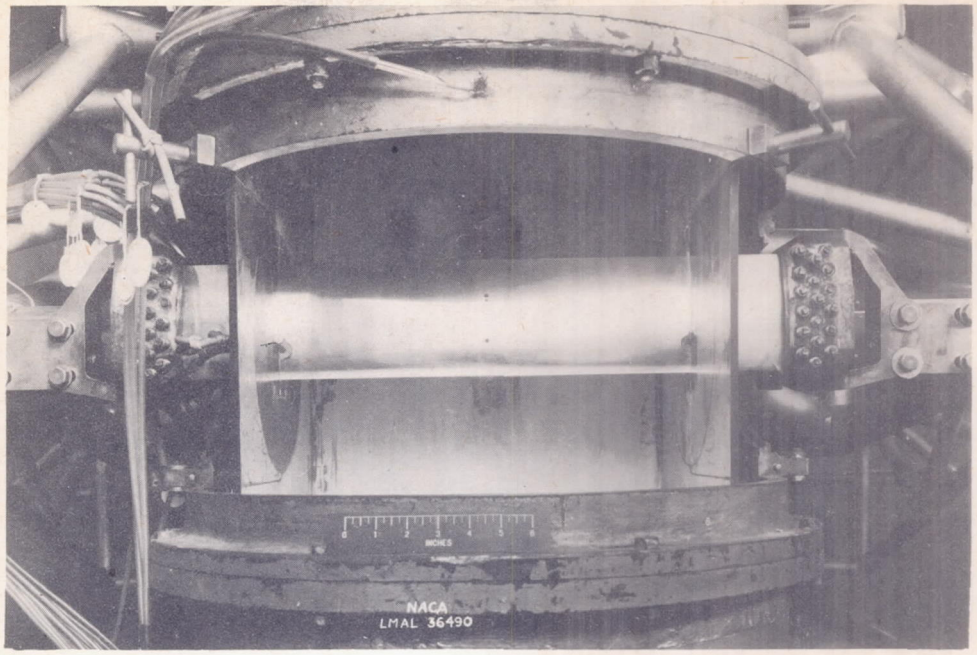
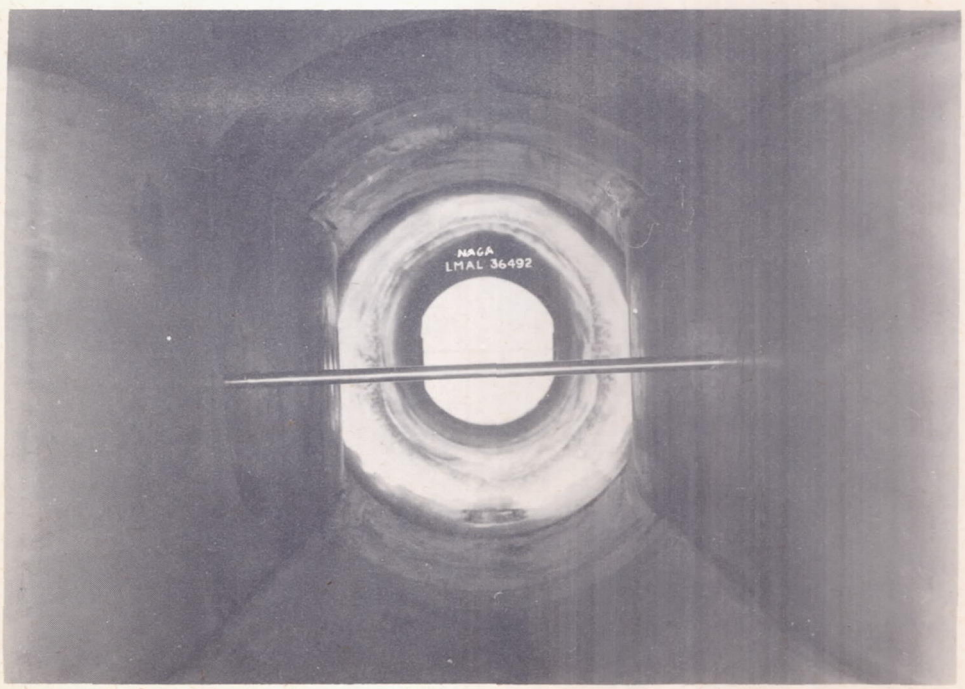
1. Stack, John, Lindsey, W. F., and Littell, Robert E.: The Compressibility Burble and the Effect of Compressibility on Pressures and Forces Acting on an Airfoil. NACA Rep. No. 646, 1938.



(a) Test section, access door removed.



(b) Test section, downstream view. CONFIDENTIAL

Figure 1.- Airfoil model mounted in modified test section of the Langley 24-inch high-speed tunnel.

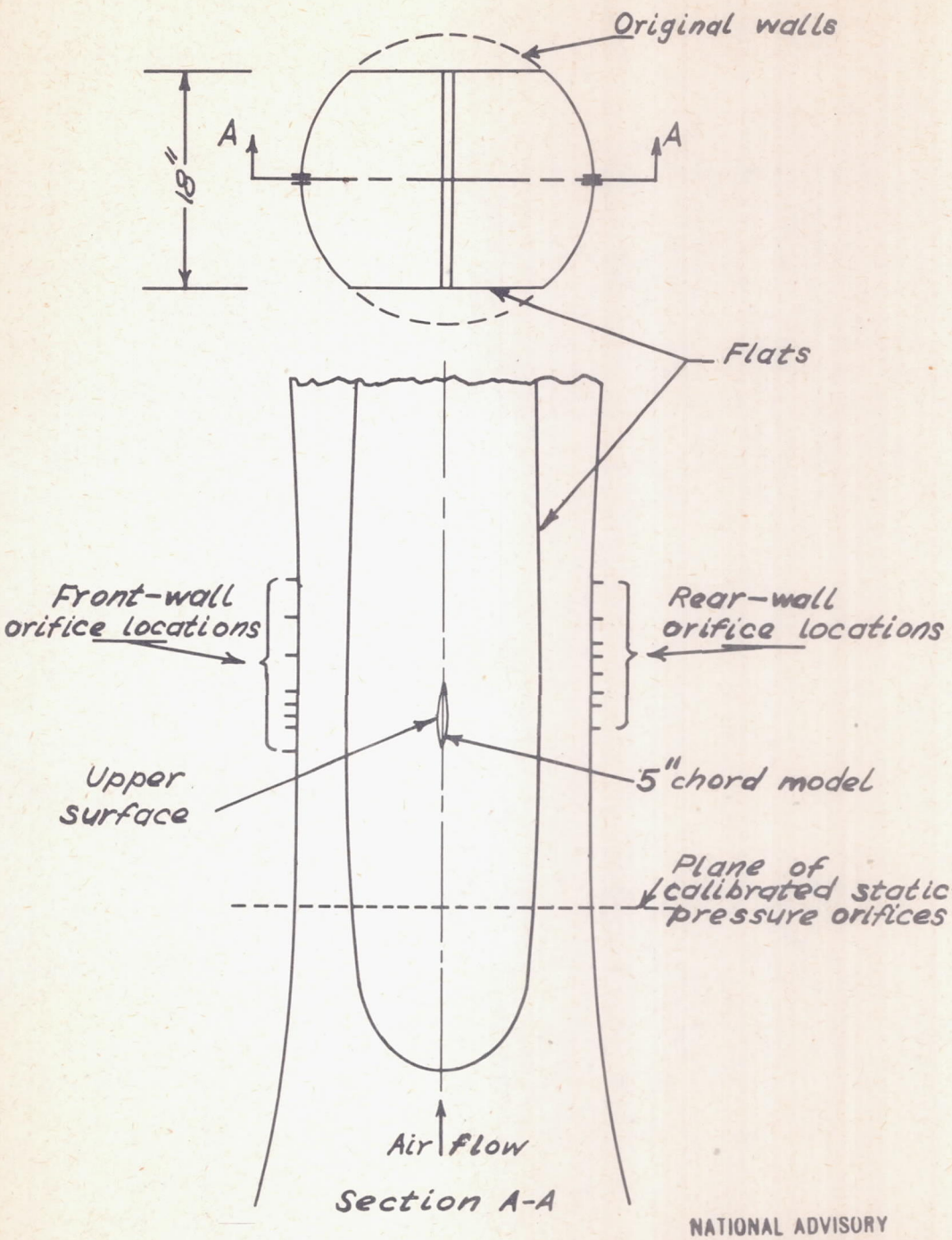


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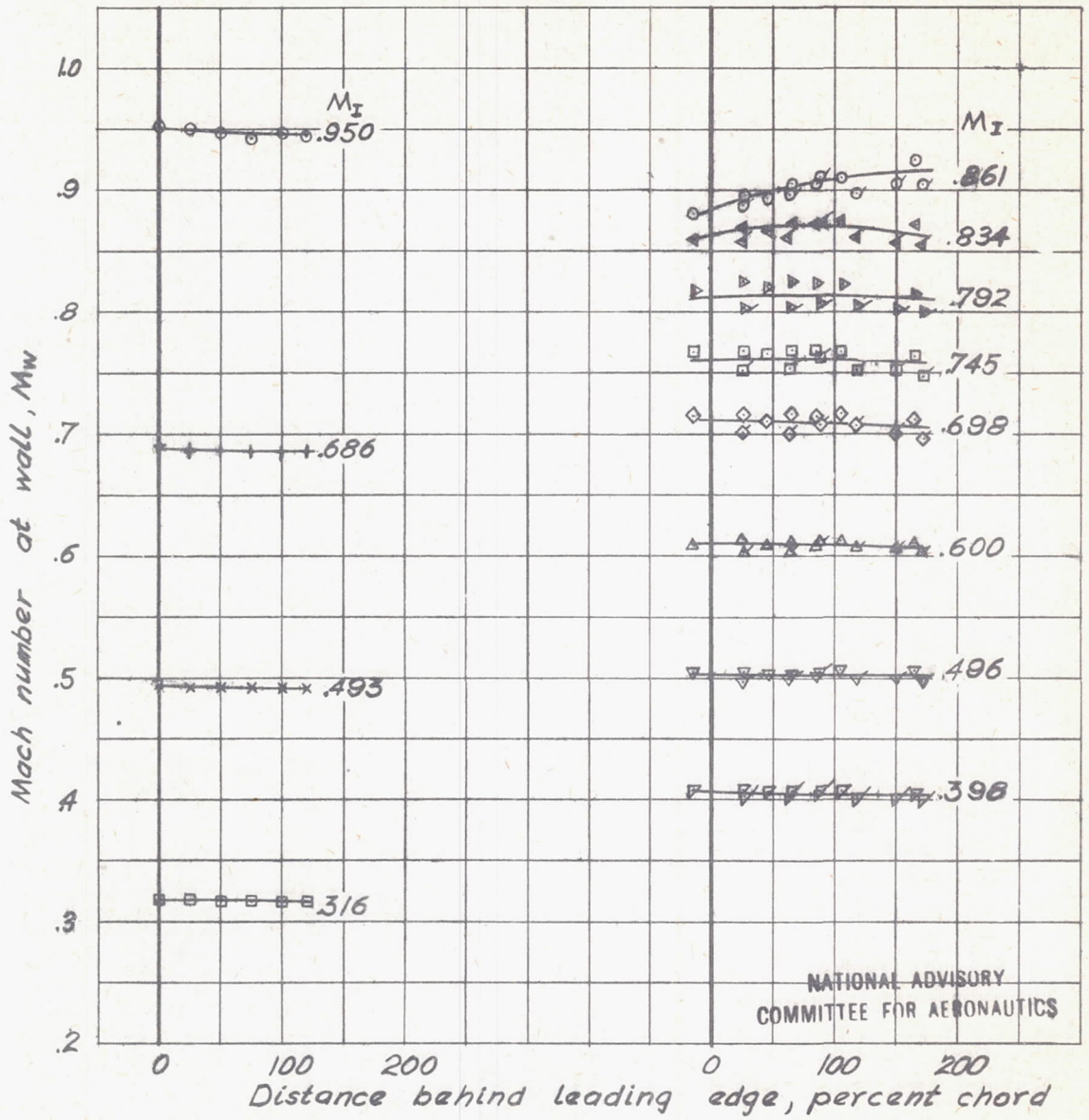
Figure 2. - Modified Langley 24-inch high-speed tunnel.



(a) Tunnel empty.

(b) NACA 16-106 airfoil section, 5-inch chord; M_{cr} = 0.82.

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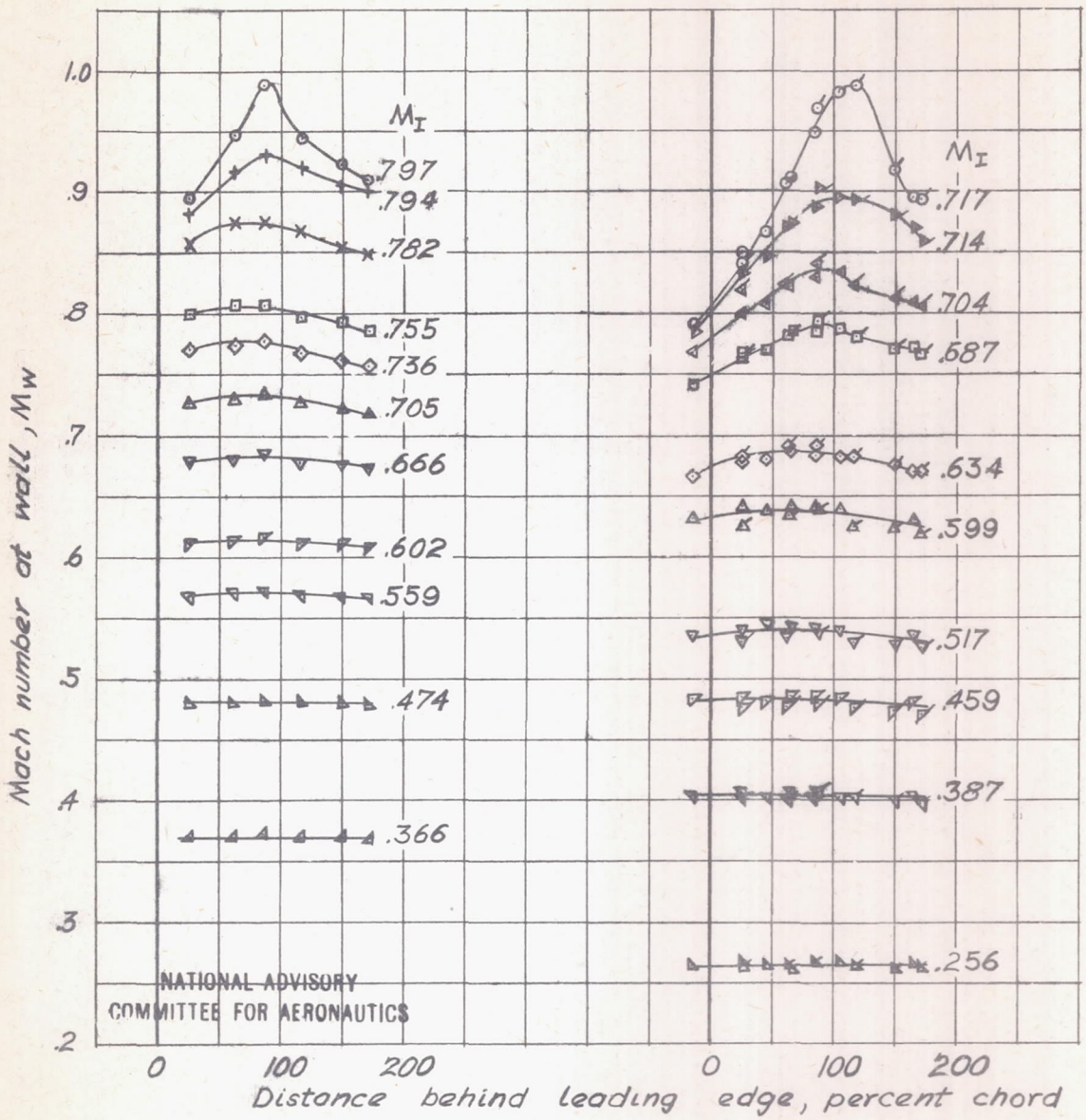
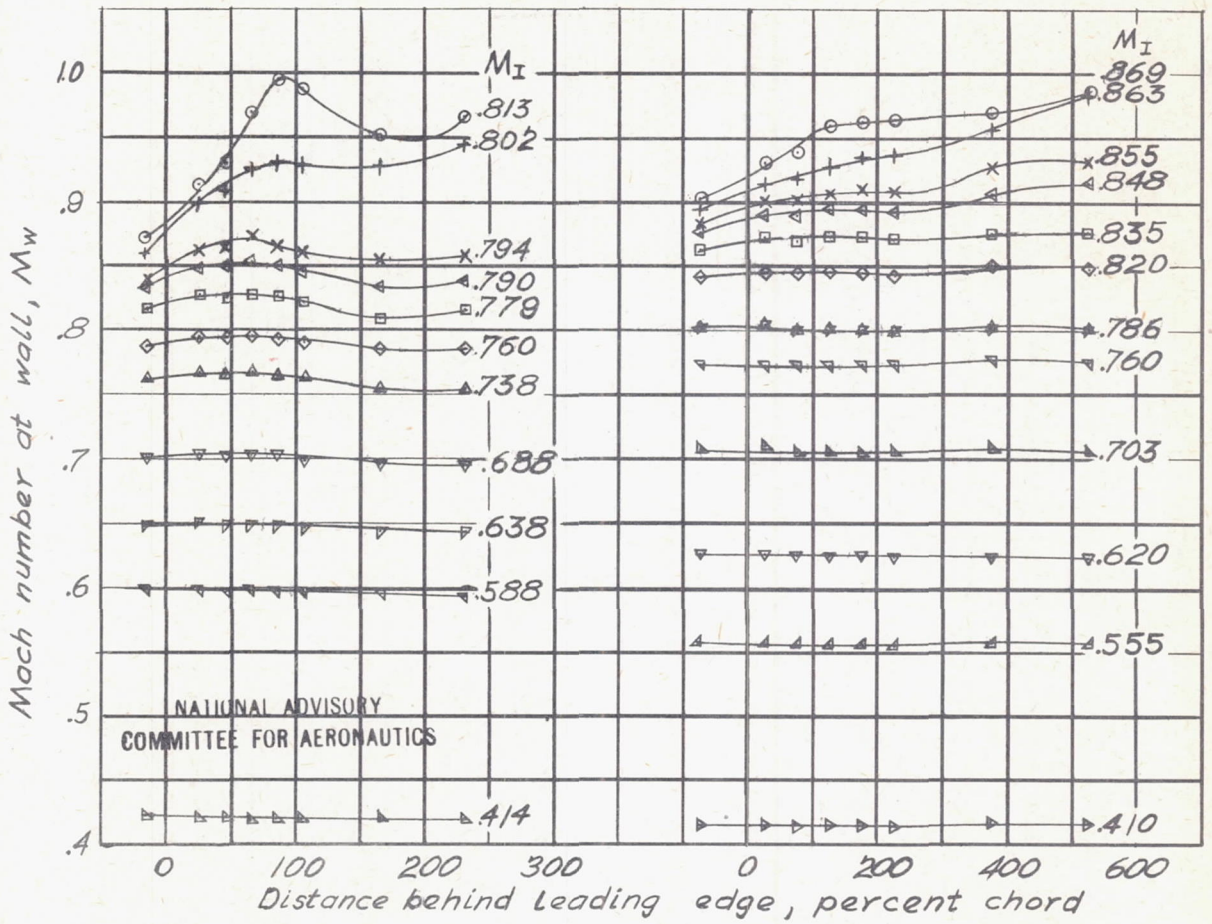
Figure 3.- Longitudinal variation of Mach number along tunnel wall.



(c) NACA 16-215 airfoil section, 5-inch chord; $M_{cr} = 0.71$.

(d) NACA 16-130 airfoil section, 5-inch chord; $M_{cr} = 0.59$.

Figure 3.- Continued.



(e) NACA 0012 airfoil section, 5-inch chord; $M_{cr} = 0.74$.

(f) NACA 0012 airfoil section, 2-inch chord; $M_{cr} = 0.74$.

Figure 3. - Concluded.

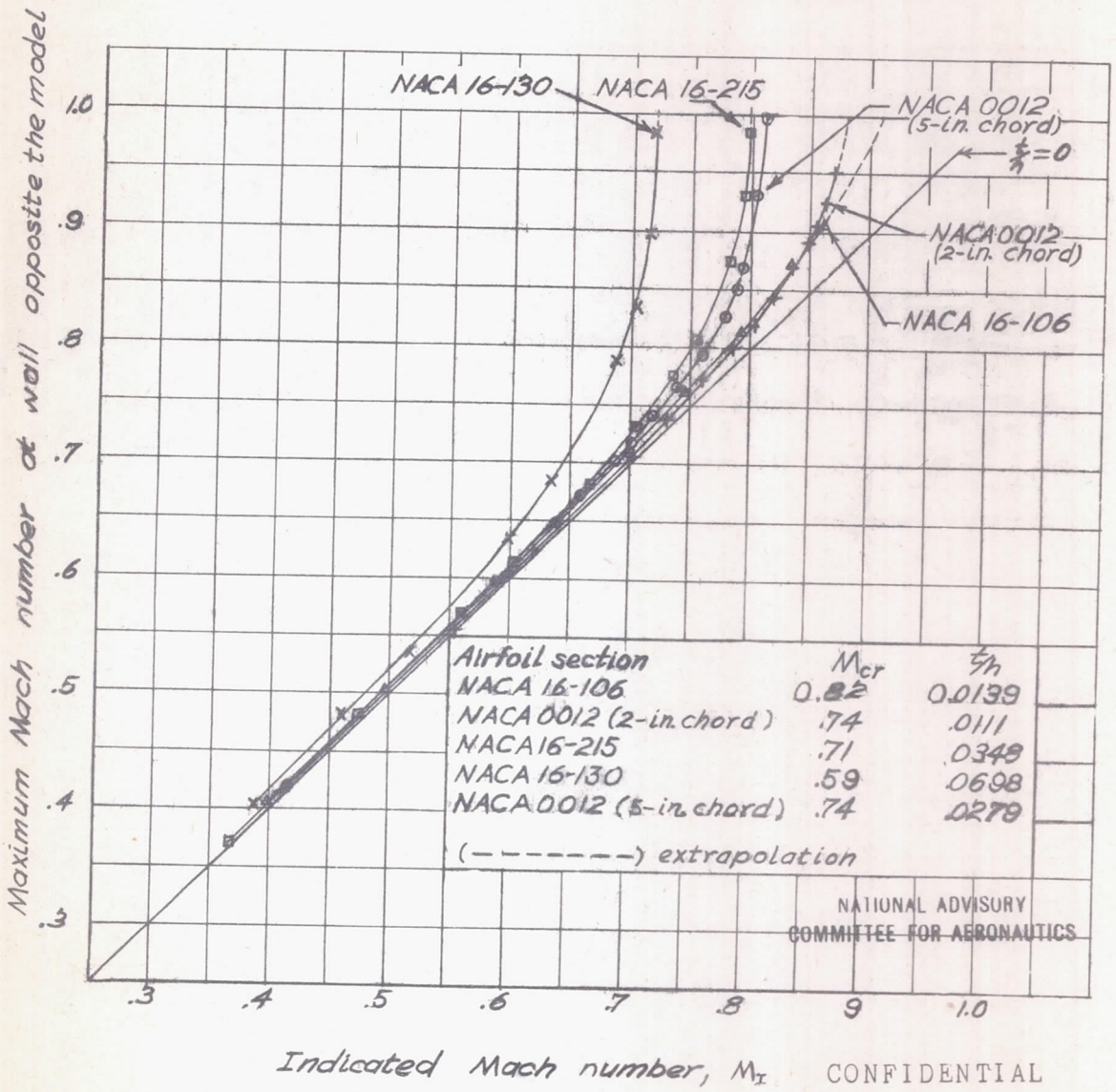


Figure 4.-Variation in the maximum Mach number at the tunnel wall opposite the model with indicated Mach number.

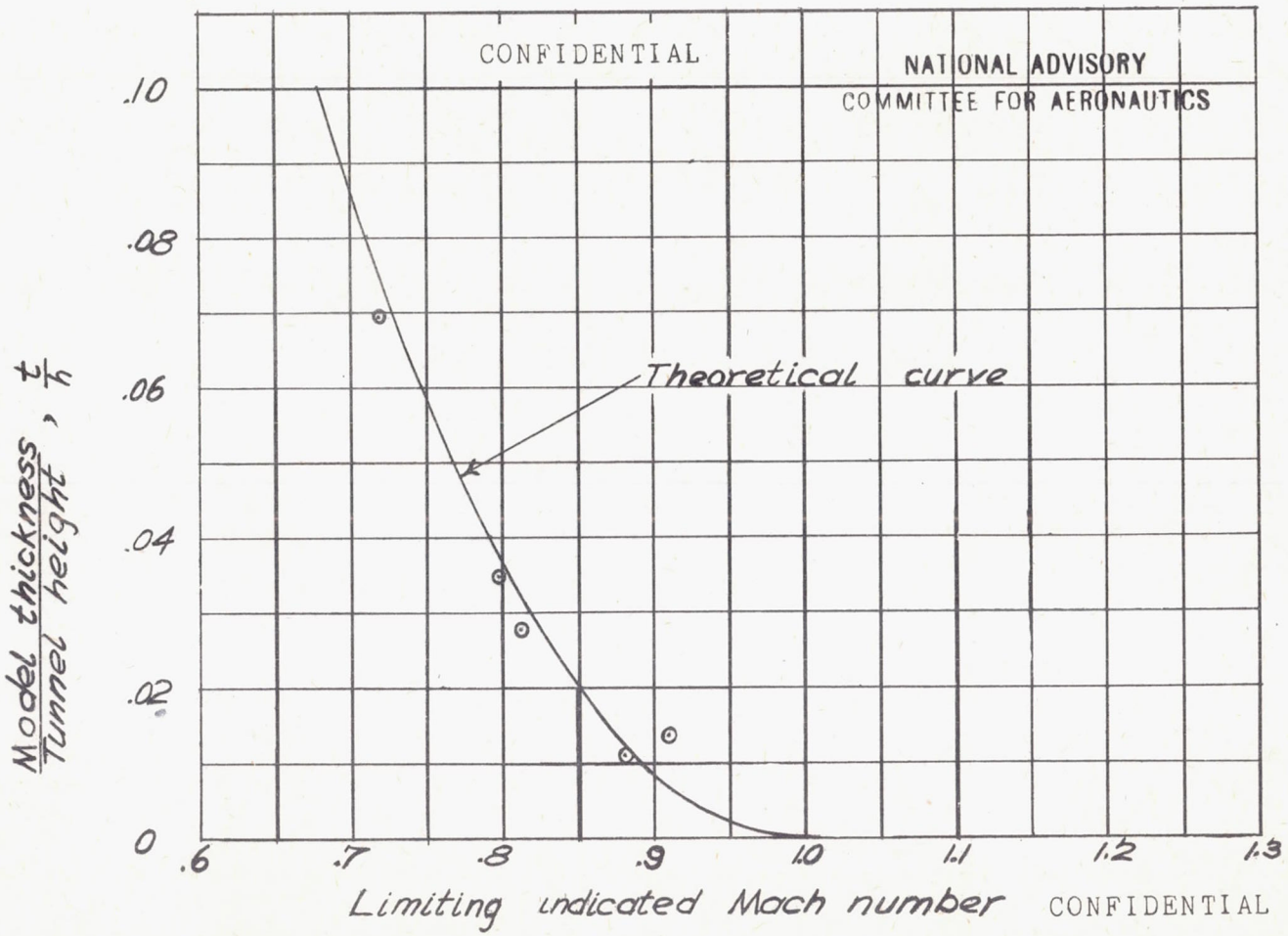


Figure 5.-Wind-tunnel limiting test Mach number.